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A review on energy conscious designs of building façades in hot and humid climates: Lessons for (and from) Kuala Lumpur and Darwin

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ABSTRACT

Emerging environmental threats originating from rapid urbanization and the associated energy shortages, negative impacts of climate change, and sick building syndromes have led to government sectors and various construction-based professional bodies recognizing the need for developing effective sustainable building design strategies. As a result, growing interest in the development of effective solutions for enhancement of the sustainable energy performance of buildings has been observed in recent years. Along this line, building envelopes that separate the indoor from the outdoor environments, and in particular building façades, play a substantial role for energy saving in buildings. Nevertheless, this study argues that there is a lack of a systematic and comprehensive analysis of the available literature regarding the energy and thermal performance of building façades based on the various possible design and technical configurations, especially in hot and humid climates. Important decisions should be made by architects and engineers during the early design stages of buildings with viewpoints to the ultimate impacts of building physics on the overall energy performance and indoor comfort conditions of buildings. With such a research gap in existing literature, in these early stages many key façade attributes may be overlooked. Hence, this study attempts to develop a state-of-the-art analysis of the existing literature about the circumstances of optimizing the performance of building façades, particularly in hot and humid climates. Likewise, the study extracts practical lessons learned from AEC industry and demonstrates the current status of utilizing energy efficient building façades in recent construction developments in Malaysia (Kuala Lumpur) and Australia (Darwin). Finally, the study draws attention to the emerging innovative solutions for the design of building façades towards improving the energy efficiency of building sector and contributing to the sustainable development of cities.

1. Introduction

The building envelope, and particularly the façade, has a large impact on the thermal and visual comfort of occupants as well as the energy demand of a building. Much of the focus of building façade design has been for the temperate climates of Europe and the United States but the requirements are much different for hot and humid climates where to date research has been scarce. Under the Köppen climate classifications, climates of Kuala Lumpur (Af, tropical rainforest) and Darwin (Aw, tropical savannah) are classified as tropical experiencing warm temperatures throughout the year and have high humidity and rainfall for at least part of the year. As the population of these cities continue to grow and more buildings - residential and commercial - are constructed, the energy demand for cooling of occupied spaces will continue to rise. The impacts of building façade design in hot and humid climates have not been properly understood. This paper presents the state-of-the art review of the energy performance of the building façades in hot and humid tropics and identifies

Abbreviations: AEC, Architecture, Engineering and Construction; DCC, Darwin Convention Centre; DSF, Double Skin Façade; ETICS, external thermal insulation composing systems; GBI, Green Building Index; IEA, International Energy Agency; KLSP, Kuala Lumpur Structure Plan; PCMs, phase change materials; PV, photovoltaic; SGHC, solar heat gain coefficient; VDSF, ventilated double skin façades; WWR, window to wall ratio

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lessons learnt from the existing research and practices for the cities of Kuala Lumpur (Malaysia) and Darwin (Australia).

2. Rapid urbanization and the need for sustainability: the case of Kuala Lumpur and Darwin

Urbanization has been occurring rapidly in the last century. The world's urban population increased from 30% in 1950 to 54% in 2014 [1]. and the rate is expected to increase over the next few decades [2], with two thirds of the world's population living in urban areas by 2050 [1]. Industrialization, mobility, technology, population and economic growth are known key contributors to rapid urbanization [3]. Although urbanization has brought positive impacts such as establishment of new settlements and towns [4], economic progress, industrial development, modern transportation systems, increased consumerism and globalization [5], its negative impacts are equally significant. Studies have long established the direct relationship between urbanization, economic growth, energy consumption and CO_2 emissions, with population density having a stronger impact on CO_2 emissions [6–10]. Supporting half of human population on less than 2% of the earth's surface, urban areas amass 80% of economic output, consume between 60% and 80% of energy, and emit approximately 75% of CO_2, making them key to tackling climate crises [11,12]. An inevitable and key phenomenon in the process of economic development, urbanization intensifies human socio-economic capital and activities, as well as energy consumption in cities. Significant savings can be achieved by reducing energy use in key components of cities – buildings, transport, and industry – as they consume 35%, 30%, and 31% of the total final energy, respectively, and are important sources of CO_2 emissions [13]. Furthermore, high density compact cities, with mixed-use urban form, are believed to be more resource-efficient than sprawl development [14].

Urbanization has indeed risen to be among the most important factors impacting sustainability, hence the widespread application of sustainable development ideals in urban and neighborhood planning. In 1987, the World Commission on Environment and Development broadly defined sustainable development as “...development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [15]. Sustainable urban development entails the presence of interdependent and desirable social, economic, and environmental qualities that apply to the past, present, and future functioning of the community [16]. A sustainable city is achieved through innovative design, collaborative management and monitoring. The new planning paradigms such as eco-cities, low-carbon cities, smart cities or zero-energy cities share key characteristics of sustainable urban development: reduced energy use, minimal encroachment on ecological spaces, fewer harmful building materials or more closed-looped waste management systems [17]. Buildings as a prominent infrastructure in the urban landscape provide many opportunities to demonstrate a city's pledge to sustainability. Sustainable building in this context refers to both a structure and processes involved that are environmentally responsible and resource efficient throughout the building life-cycle using ecological principles, social equity, and quality value, and which promotes a sense of sustainable community [18].

As with its counterparts in other developing countries, the rapid rate of urbanization continues to characterize development in Malaysia. Its average urban population growth rate of 2.0% was among the fastest in the East Asian region. In 2010, urbanization rate in Malaysia reached 71%; by 2014 this rate increased to 74% [19]. Kuala Lumpur, which is the capital of the nation, is the most populous and fastest growing metropolitan area with an estimated population of 1.73 million in 2015 [20]. The larger urbanised area officially known as the Greater Kuala Lumpur, meanwhile, is home to an estimated 7 million people [1]. Given the existence of a long-run co-integrating relationship among CO_2 emissions and energy consumption with affluence and population growth [21–23], it is projected that energy consumption and the associated CO_2 emissions will escalate due to its high urbanization rates as development of Kuala Lumpur progresses.

The most spectacular change in the urban landscape of Kuala Lumpur was attributed to the Kuala Lumpur City Centre (KLCC) project which begun in 1992. Dubbed as the “city within a city” and the largest real estate development in the world at the time, it included the world's tallest building, the Petronas Twin Towers [24]. All buildings in the complex which were built and maintained at world class standards have enabled them to command premium values. KLCC is currently the most prominent element and point of reference in the Kuala Lumpur urban landscape where many new and tall buildings are concentrated. The spread of expressways and big-box shopping centers in Kuala Lumpur in the meantime, appeared to follow the trends already observed in the US and elsewhere [25]. While the iconic colonial-era buildings in Kuala Lumpur were mostly designed to use local resources and adapted to the local hot and humid climate, most of the newer buildings which began to be erected throughout the city in the late 1990s and early 2000s used glass shells. They neither paid sufficient attention to the tropical climate nor took appropriate measures to conserve building energy [26].

Since the Rio Summit in 1992, serious efforts to integrate sustainable objectives into urban development plans in Malaysia were evident in the National Urbanization Policy (NUP) (2005) [27] and its corollary National Physical Plan (2009) [28], as well as the lower tier State Structure Plans and Local Plans. In this context, the formulation of the Kuala Lumpur Structure Plan (KLSP 2020), while embodying the goal of the NUP that emphasises a balanced social, economic and physical development within urban areas, incorporates further planning approaches for sustainable urban development that are current and best practiced. These include the maximized use of existing infrastructure through urban regeneration and redevelopment, compact urban form and transit-oriented development. Additionally, the Kuala Lumpur City Hall adopts the various Guidelines prepared by the Federal Department of Town and Country Planning Malaysia as tools to address the objectives and planning requirements for sustainable urban developments. The Guidelines for Green Neighborhood (FDTC 2012) [29] for example, which cover three major design criteria of smart location, neighborhood pattern and design as well as green infrastructure (greenfrastucture), identify buildings that meet the requirements of a green neighborhood as: (i) energy efficient, (ii) use recycled materials for construction, (iii) engage in sustainable building planning and management and (iv) utilize green technology innovations. As the local planning authority, the Kuala Lumpur City Hall takes a voluntary approach to green features in buildings, as no regulations require such features yet in Malaysia.

The integration of sustainable objectives into development plans in Malaysia is corroborated in urban policies, plans and strategies with local planning authorities voluntarily incorporating green features in buildings. While the codes of practice and standards for green building are not mandatory in the country, the Green Building Index (GBI) is frequently used as a rating tool for green buildings and township development. The six criteria of GBI include: (i) energy efficiency, (ii) good quality internal environment, (iii) sustainable building planning and management, (iv) use of recycled materials for construction, (v) water efficiency and (vi) utilize green technology innovations. Increasingly green buildings play an important part in sustainable urban development in Malaysia.

Compared to many developed countries, Australia demonstrates a very high urban population with 89% in 2014 [30] and 65% concentrated in the capital cities [31]. In recent decades, very high immigration into Australia contributed to 60% of the nation's population growth [32]. The Australian population is expected to quickly grow to as much as double the current population by 2050 [33,34]. The large cities in Australia are expected to absorb the bulk of this growth, gaining 72% of the predicted national population growth by 2056, or an

Table 1
Building façade classification based on key performances.

Major categorization	Sub-categories	Thermal performance	Weaknesses/limitations	Ref.
Stone façade	Marble curtain wall	1. Little insulating value	1. Pose a serious safety hazard during the fire	[54,55]
	Brick masonry curtain wall	1. With high thermal mass and the thermal performance could be improve by the higher inhomogeneity	1. Pose a serious safety hazard during the fire	
Metal façade	Aluminium curtain wall	1. Thermal performance depends largely on the fastening unit design	1. Limited resistance to deformation	[56,57]
	Steel curtain wall	1. Normally has limited insulation performance 2. Reducing thermal bridges can achieve higher energy efficiency	1. Limited resistance to deformation	[58]
Glazing façade	Single Glazing curtain wall	1. Higher frame ratio can be a cause of the lower thermal performance of the curtain wall system 2. Poor thermal performance	1. Light Pollution 2. High cleaning costs 3. Face the danger of bursting	[59,60]
	Double Glazing curtain wall	1. The structural glazing systems studied provide better thermal performance than other glazing curtain wall	1. Light Pollution 2. High cleaning costs 3. Danger of bursting	[61]
Vegetated façade		1. The high capacity to intercept the direct solar radiation, which implies representative reductions on the external surface wall and indoor temperature	1. Apoptosis of vegetation by unreasonable management or facility errors	[62]
Solar Façade	Semi-transparent and Opaque facade	1. Can reduce or eliminate fossil fuel requirement to provide	1. Higher construction costs 2. Low conversion efficiency	[63]
		2. A larger proportion of a building's surface area for energy generation 3. Improves indoor environments for occupants		[63,64]
Phase change material (PCM) façade		1. Can keep the indoor temperature within the comfort range 2. Can minimize the peak cooling/heating loads and reduce operation costs.	1. Insufficient strength	[65]
Kinetic façade		1. Reduce over-lighting due to control of direct solar penetration 2. Automatically responding to micro-climatic variations	1. Higher construction costs 2. Higher maintenance costs	[66]

additional 10 million people [35].

The building sector is a large contributor to global warming. According to the Australian Institute of Architects, commercial and residential buildings account for 23% of Australia's greenhouse gas emissions [36]. By the nation adopting energy efficiency practices into Australia's buildings, the institute believes that energy demand of the building sector can be halved by 2030 and by 2050 a reduction of 70% can be achieved, leading to a $38 billion increase in GDP.

The city of Darwin was founded in 1869, though originally called Palmerston, the name was changed in 1911. After gold was discovered in the nearby town of Pine Creek in 1871, the population of Darwin grew quickly. However, during World War II, many public buildings were destroyed by Japanese bombings. Another event, Cyclone Tracy, in 1974, again caused havoc on the city's infrastructure and destroyed 70% of all buildings. Having been rebuilt twice due to these significant events, Darwin is structurally one of Australia's youngest built capital cities [37].

Darwin, which is located at the top end of the Northern Territory, is one of Australia's three largest tropical cities. The population has increased from 39,000 in 1971 to more than 136,000 in 2013 [38], with a population density of 0.43 persons per ha, representing 55% of the total Northern Territory population. Over the 10 years leading up to 2010, annual population growth for Australia was between 1.3% and 2% for Darwin [39]. The city is predicted to experience significant population growth to reach 240,000 by 2056. This substantial urban growth poses serious implications on productivity, liveability, and sustainability.

Darwin was rated as being the most sustainable city in Australia (along with Brisbane) according to the Australian Conservation Foundation [40] and the city continues to demonstrate its environmental stewardship. In late 2011, the Darwin City Council published its Climate Change Action Plan 2011–2020, which outlines the needs to employ energy efficient practices for new buildings as well as refurbishing current ones [41]. The Territory government also has recently earmarked $100 million to revitalize the Darwin's central business district, (and could be matched through the Commonwealth's City Deals program), which includes sustainable urban design that focuses on the local climate to make the city more comfortable and energy efficient [42].

3. Building façades

3.1. Overview

Currently, the building sector is responsible for approximately 40% of the global energy consumption in many developed and developing countries [43,44]. As a result, improving the energy efficiency in buildings has become one of the key agendas of governmental sectors towards the sustainable development of cities.

Building façades are one of the most technologically challenging, multifaceted and interdisciplinary components of a building. From an architectural design point of view, the façade is one of the most important components of a building for showcasing the building's aesthetic values and its architectural expressions. From an engineering perspective, building envelopes, including the façade, play a significant role in protecting (maintaining) the indoor thermal conditions and improving the sustainable performance of buildings. In a nutshell, façades are firstly responsible for the appearance of buildings and secondly, for how it performs [45]. Indeed, an efficiently designed building façade can make buildings function more successfully for its occupants and environment. Likewise, building façades can impact the level of users' satisfaction from their indoor living and/or working environment. Generally, design of building façades is a complex issue and demands an interdisciplinary approach, ideally requiring a team of architects, engineers and environmental scientists to collaborate towards achieving the optimum design. Designing a building façade entails the consideration of several factors including outdoor environment and microclimatic conditions, indoor ambient and spatial characteristics and occupants' needs [46].

3.2. Classifications and technical characteristics

Building façades are generally classified into two categories, namely opaque and glazed façades. Opaque façades are predominantly made of solid layers of materials such as masonry, concrete, stone, etc. Glazed façades are primarily made of transparent or translucent glazing materials [46]. Table 1 provides a succinct overview of building facades classifications based on their key performances.

Sustainable design of some building façades as part of building envelopes requires careful consideration of various building parameters that could affect indoor natural ventilation, visual comfort through daylight, thermal comfort and ultimately the overall energy performance of the building. Mirrahimi et al. [47] identified a number of parameters that need to be considered when designing building façades. These include: building physics (including form, height, length, width, etc.), building location (including building orientation and surrounding context), external/internal walls and materials, thermal insulation of façades, windows, external/internal glazing, window to wall ratio (WWR), and external shading. Building façade designs that simultaneously achieve optimum energy use and acceptable constructability can become very complex, challenging and multifaceted [48]. Among the key components of façades, several studies report that façade openings considerably affect the performance of buildings compared to the other key constituents [49,50].

In recent years, building façade design has rapidly evolved to respond to the new aesthetic expectations of architects towards more complex and sophisticated geometrical forms. However, the sustainable performance of buildings and their responses to the local climate should always be an important goal of the design. As a result, several studies have recommended climate-based façade design approach to ensure more adaptability and higher energy efficiency [46,51]. In Kuala Lumpur and Darwin with hot and humid tropical climates, building façades should be designed based on key sustainability and green design principles in order to protect the indoor ambient from the harsh climatic conditions. This should lead to improved thermal performance, optimized used of daylighting and natural ventilation and improved comfort conditions of indoor spaces.

Looking at the optimized daylight harvesting by building façades in hot and humid climate [52], the following main recommendations are extracted:

- Solar heat gain reduction
- Glare control
- Deep daylight penetration
- Uniform daylight distribution

Admittedly, to date research on energy efficient building façades design in hot and humid climate has been inadequate. Based on the information from limited literature, the following basic prescriptive guidelines have been identified:

- Decrease heat gain during daytime and increase heat loss during night-time
- Decrease internal heat gain of indoor ambient
- Select building façade orientation with viewpoint to the surrounding context and microclimatic parameters, particularly according to sun and wind orientations
- Improve the thermal capacity of building façade
- Use the most appropriate high albedo values for façade materials
- Control solar radiation and provide sufficient shading while receiving adequate daylight for indoor ambient
- Enhance air movement and cross ventilation

From a technical viewpoint, there are always the potential risks of conflicts in building façade design that can occur during the iterative design process of considering all influential parameters/guidelines, discussed above. For instance, increasing WWR to achieve optimum daylighting may be effective in decreasing the energy consumption derived from the use of artificial lighting; however, this approach may increase solar gain, which in turn increases use of energy for cooling. Likewise, increased reliance on natural ventilation may result in an unacceptable humidity level in occupied spaces [53].

4. Impacts of building façades on energy performance

4.1. Overview

Many researchers have highlighted the impact of building envelope on the energy performances of the structure [67–75]. Façades, as an important component of building envelope, play a significant role in this regard, particularly in high-rise buildings [76]. This section discusses the impact of materials, insulation, geometry, orientation and openings on the façade thermal performance. In this regard, this study also attempts to correct and clarify the misconceptions about energy efficient building façades that exist in the Architecture, Engineering and Construction (AEC) industry.

As previously highlighted, performance of building façades – comprising elements such as windows, shading devices and opaque components – has a significant effect on building energy consumption for heating, cooling, ventilation and lighting [77]. To optimize the façade performance, various aspects need to be carefully considered from early design stages to avoid further needs for supplementary mechanical/electrical systems to compensate for design deficits [78].

Many conventional building façades are not optimally designed for energy performance and thermal comfort [79]. On the other hand, energy-efficient façades are responsible for significantly reducing carbon emissions during the operational phase of a building and are expected to contribute to the global target of tackling climate change [80]. The U-value, solar heat gain coefficient and solar reflectance are among factors affecting façade performance [81].

Researchers have started investigating the potential of advanced design of façades [74] for reducing building energy consumption and for energy generation. This has enabled incorporating the notion of advanced façades into net zero and even positive energy buildings [78]. The concept of climate adaptive building shells [82,83] was introduced to highlight the role of façades in improving building energy performance and reducing environmental impacts.

Introducing advanced energy-efficient façades in contemporary buildings is a challenging endeavour due to often unavoidable conflicts mentioned previously. On the other hand, many features of building envelopes need to be revisited to facilitate cost-efficient energy savings in buildings. These revisions need to be implemented carefully to ensure users' satisfaction and maintain quality of life.

4.2. The impact of materials

Materials used in building envelopes play a significant role in shifting the building towards sustainability through energy-efficient façades [81]. The materials also influence indoor thermal comfort, for a review of the effect of materials on thermal comfort please refer to [84]. Insulation is used in both heating [85] and cooling dominated climates as a way to save energy [86]. New alternatives have emerged to improve upon contemporary systems to enable them to contribute towards development of a sustainable future. For façade renovation purposes, one such alternative is lightweight façade cladding systems which are considered to be a better alternative to external thermal insulation composing systems [87]. Vegetated walls are an attractive option from an environmental point of view. These systems are also beneficial in terms of social and economic concerns. Application of vegetated walls in both new and existing buildings are found to be an effective energy-saving approach specifically in terms of cooling energy reduction [88].

Thermal mass can be used as a means to reduce and time-shift peak cooling loads [89–91]. Cooling of the thermal mass is needed at night and is more effective with larger diurnal temperature variation and night ventilation. Cooling a building this way is useful for reducing the temperature but may still leave humidity levels at unacceptable conditions [92]. The Trombe wall is a thermal mass design where a thermally massive wall is placed behind a glazed façade that can be used for convective cooling or solar heating, respectively, of the occupied space and one that has been extensively researched [93,94]. It has been shown to be effective in tropical climates for temperature control [95] but their overall usefulness in tropical regions remains limited.

The concept of phase change materials (PCMs) has been the subject of investigations for various applications. One of the potential applications of PCMs is in buildings as building materials due to their capacity to store and release heat at a relatively constant temperature. Application of PCMs in building envelopes is aimed at enhancing its thermal storage capacity and therefore reduces the fluctuation of indoor temperature [96]. Correspondingly, use of renewable and non-renewable materials can be rationalized [97]. Application of PCMs in transparent building components has recently been promoted [98,99]. Proper selection and incorporation of advanced materials in building façades is aimed to result in considerable energy savings. However, more research on PCMs needs to be carried out to make them an attractive option. This includes enhancing PCM chemical stability, addressing the issue of PCM super-cooling and improving PCM encapsulation technology that prevents leakages [100].

4.3. The impact of insulation

Thermal insulation is perhaps one of the simplest and most cost-effective measures of reducing heat exchange between the interior and exterior of buildings in all climate conditions [101–105]. In cooling dominated climates proper insulation of building envelope plays an important role in reducing the energy required for cooling and leads to smaller HVAC system requirements. Proper insulation in this context refers to selection of insulation materials, optimum thickness and optimum installation locations. A recent study [106] identified the inversely proportional relationship between insulation thickness and respective material costs. The study highlighted that increasing the thickness of insulation layers is only effective up to a certain limit; exceeding this limit would result in significantly elevated cost which could not be recovered from savings gained through reduced building energy consumption over time. This is of course in line with the basic engineering concept of insulation *critical thickness* [107]. Al-Sanea [108] found that having the insulation layer on the outside led to better results for cooling dominated loads.

There is a more recent push to use recycled or environmentally friendly materials for insulation as opposed to typical materials such as rockwool or polystyrene [109–111]. For a complete review on sustainable insulation materials please refer to [112].

Use of cavities as an insulation approach for building envelopes is widely spread. Researchers expressed the importance of utilizing ventilated double skin façades according to their capabilities in preventing building overheating through absorbing solar radiations [113,114].

A number of emerging insulation and material for building façades have been developed. Aerogel [115] – a synthetic porous ultra-light material – provides high heat transfer conduction resistance whilst ventilated glazing [116] and vacuum insulation panels [102,117–119] limits heat transfer through controlled convection. Smart windows [120] manage solar heat flux by controlling the level of opacity (controlled optical properties) [121]; examples include self-adjusting electrochromic glass [122] and liquid crystal windows [123]. Such systems can be coupled with vegeted façades [124] which are found to be effective in reducing building operating temperature while ensuring the occupants comfort. On the contrary, other studies [52] claim that while proper insulation in building façades can drastically reduce the peak cooling loads, its impacts on the overall energy consumption is not highly significant in cities such as Kuala Lumpur where the annual average dry bulb temperature is 26.9 °C.

4.4. The impact of geometry and orientation

Various factors such as building typology, climate, materials, solar heat gain coefficient, thermal conductance, visual transmittance, etc. are considered during the design of building façades/fenestrations/ openings. On the other hand, building geometry and orientation parameters, which play equally important roles in façade performance, are often ignored [125]. These parameters include but are not limited to windows to wall ratio, building orientation and openings, shading devices configurations and internal spacing arrangements [125]. As the orientation and geometry of buildings and their fenestrations account for considerable energy use throughout the building lifecycle, it is essential to thoroughly consider and design these elements during early design stages [125]. While control of solar heat gain is highly dependent on the urban morphology, building geometry and orientation, there are other aspects such as the types of integrated exterior/ interior shading devices and glazing levels that similarly contribute to the levels of control [52]. In cold climates it is preferable to reduce the building envelope area as more heat escapes than be gained through solar radiation; in warm climates this relationship is not as clear [106].

4.5. The impact of openings

Openings, as key elements of building façades, allow for natural lighting and ventilation, visual connection to the exterior and heat penetration (solar radiation) [76]. Windows operation usually affect other parameters [126]; for instance provision of view to the outside through an opening may compromise building thermal performance, acoustic conditions and ventilation configurations. Therefore, the need for adaptive, self-adjusting building façades is highlighted. Pairing shading devices with suitably composed and oriented openings is also considered as an effective approach towards preventing excessive solar heat gain resulting in significantly reduced building cooling loads [127]. This is particularly effective in hot climates. Incorporation of advanced materials/components/technologies such as electrochromic and photovoltaic (PV) integrated glazing [128,129] and PV-incorporated automated shading devices with this approach is expected to have a considerable impact on the overall building energy performance.

5. Classification of the main sustainable building façades in hot and humid climate

According to Aksamija [46], there are two broad categories of façades: (1) glazed façades, which are constructed mostly from transparent or translucent glazing materials within a metal frame, and (2) opaque façades that are made from sturdy materials such as concrete and steel and may have punched-hole openings or windows. Sustainable façade design strategies for warm climates, which are space cooling dominated, should be focused mostly on reducing solar and external heat gains while at the same time allowing natural daylighting and using natural ventilation for cooling if possible.

5.1. Glazed façade

Glazed building façades are referred to as curtain walls since they are not structural components of the building. Various types of glazing systems can be used including multiple panes with different gases between them, tinting, low emissivity coatings, and several framing materials that all affect the thermal performance of the façade. In general, glazed façades provide less thermal insulation than opaque ones.

High-rise buildings often have glazed façades. Nevertheless, in the tropical environment this can lead to a large amount of unwanted solar heat gain. Some amount of glazing is necessary to promote human (visual) comfort and productivity [46]. Without sufficient daylighting, artificial lighting has to be provided and can lead to higher electricity

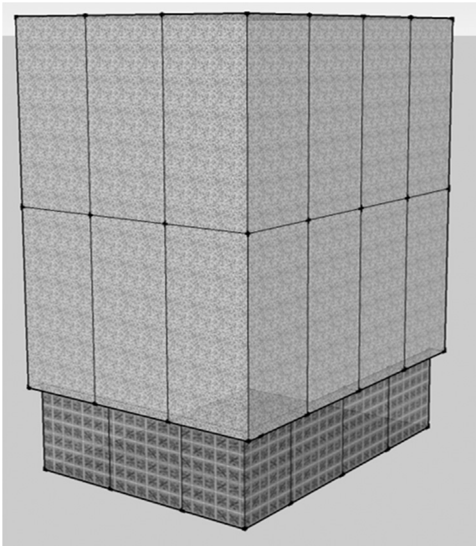

Fig. 1. Building with a fully glazed façade. This type of construction is not typically recommended for tropical locations because of the admission of copious amounts of solar radiation. There are ways to reduce solar heat gain such as using low emissivity or tinted glass, but would still not be recommended without the use of shading.

consumption and excess heat that has to be removed from the building adding to the cooling load [130,131]. As discussed in previous section, altering the transparency of the façade glazing in conjunction with shading and light shelves can help to optimize the energy efficiency with regards to lighting and the cooling load (See Fig. 1).

Exploring the urban contexts of Kuala Lumpur and Darwin, numerous building façades were designed using simple single glazing for the purpose of transparency which significantly impacts the cooling loads. This indicates low consideration to the impact of solar heat gain and visible light (heat) transmission during the design and development of building envelopes [52].

Likewise, it should be noted that in the tropical climates, appropriate glazing commonly leads to more significant impacts than external integrated shading devices. Glazing potentially has the ability to reduce solar heat gain of both direct and diffuse radiation, while external shading only protects the indoor ambient from direct radiation [52]. Recent studies reported that the application of high-performance double low-e glazing is strongly recommended to decrease the solar heat gain coefficient.

One type of façade growing in popularity in temperate climates such as Europe is the double skin façade (DSF) [132]. A DSF consists of two glazed layers on the side of a building with a ventilated air gap in between them. The attributes of the glass layers can be different from each other such as the number of panes, tinting, low-e glass, etc. The space between the skins can be mechanically or passively ventilated or a hybridization of the two. The purpose of the gap is to provide a temperature buffer from the external wall that is exposed to the elements and the wall that edges the occupied space and reduce the energy demand of the HVAC system. It also acts to reduce external acoustical noise from entering the occupied space.

There has been recent work to identify the benefits of a DSF specifically for tropical and sub-tropical climates, where the only aim is to reduce heat gain of the building to a minimum [79,130,131,133–138]. One of the more common options for DSF in hot, humid climate is to install operable shading devices between the skins to absorb some of the solar radiation and ventilate the gap to reduce the amount of heat that enter the occupied spaces.

There is a strong link between the ventilation mechanism which can be natural, forced or a combination of the two and the performance of the DSF. The double skin façades can be classified into four main categories as window façade, shaft-box façade, corridor façade, and multistorey façade. The configuration of DSFs with natural ventilation could significantly save energy and provide a better thermal comfort in high rise buildings in hot and humid tropics [138].

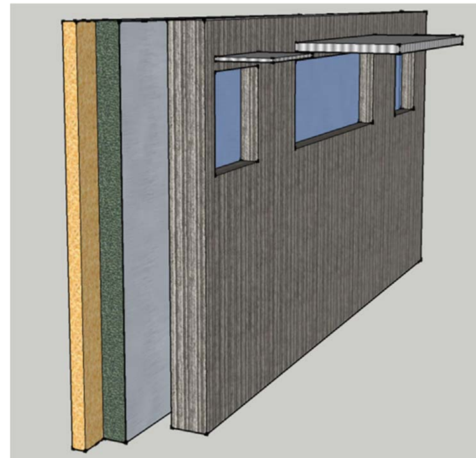

Fig. 2. A cross-sectional view of a typical opaque façade for tropical design. The exterior is concrete with a small WWR and heavy shading over the windows. Behind the exterior layer there is an air gap to prevent heat conduction to the inside, followed by a radiant barrier, thermal insulation and then a lightweight material for the indoor wall.

5.2. *Opaque façades*

The materials that make up an opaque façade and the window-to-wall ratio (WWR) are two important factors in the thermal performance of a building. The cross-section of a typical opaque façade used in the tropics is shown in Fig. 2. Heat gain through a building envelope is by solar radiation transmitted through windows, air leakage between the internal and external air and thermal conduction through the opaque walls and the windows [46]. In general, the higher the WWR the more solar heat gain a building will have along with a larger cooling load [130,139].

For opaque façades, the installation of insulation is also a possible option that can reduce heat gain and improve energy efficiency. For air conditioned buildings, insulation can be used to reduce heat gain from the occupied space through the external walls and thus reduces the cooling load [139–142].

The albedo of the exterior opaque material also has an impact. In hot climates that are cooling dominated it is best to use outside coatings that are more reflective that limit solar absorbance and therefore transmission into the occupied space [143–146]. For an existing concrete building, applying a reflective coating is also a cost-effective retrofit [147]. The reflectivity of the coating can be enhanced by the incorporation of reflective additives [148,149], increasing reflectivity was found by increasing the particle size of the additives [150]. The application of reflective coatings can also help to mitigate the heat island effect in urban areas, for a comprehensive review, please refer to [151]. Retro reflective surfaces have been shown to be more effective than diffusely reflective ones [152]. For climates that have a cooling and heating requirement, the savings from reflective exterior surfaces during the cooling period can more than compensates for the heating period penalty in some locations [153]but has a negative overall effect in others [154]. One issue with high albedo buildings is that, even though they reduce the internal heat gain, the reflected solar heat gain can add to the external temperatures [155,156] and reduce air quality [157,158].

Vegetation can also be used to create a bio-façade. These types of façades can work well in hot and dry climates to limit the solar heat gain to building by providing shading and insulation, and creating evaporative cooling effect and variation of the breezes going through a dwelling; however they can also lead to higher internal night time temperatures [159]. Certain vegetation with a higher albedo will have the additional effect of reflecting more solar energy away [148]. In very humid environments vegetated and green roofs could be relied upon to reduce the temperature; however resulting humidity level can be unacceptably high [160].

In one particular case study, the impact of blue trumpet vine as external vegetated façade on west facing wall was investigated for a house in tropical Bangkok [160]. The results showed that the maximum day-time temperature reduced by up to 6.78 K with an average difference of 2.27 K compared to outside air temperature. However, there was an increase in relative humidity increased to the maximum and the night-time temperatures were found to be higher compared to outside air temperature. Moreover, the temperature reductions during day time did not reach to comfort zone temperatures.

6. Recent attempts at optimizing the energy performance of building façades

With the recent trend of making buildings more energy efficient, and since the envelope accounts for a large amount of heat gain, it is no wonder there has been much research into façade design. The pool of knowledge for tropical architectural design is also growing. The area getting the most current research is the DSF.

6.1. Double skin façade

The DSF seems like a sensible choice for hot climates since the main objective is keep heat out. By heating the space between the skins and then ventilating the hot air out, much of the solar energy can be prevented from entering the occupied space. There have been many simulations demonstrating the effectiveness of the DSF over the more common single-glazed skin façade on cooling loads in tropical and subtropical climates [130,133–138]. However, there have only been a few laboratory studies [135] and field studies [130,133,135] on the topic, demonstrating the need for more research in the field.

There are many aspects to consider when designing a DSF. For instance, [133] looked at the difference in the cooling demand of a fully air-conditioned office building having DSFs and a single glazed façade in subtropical Hong Kong. They varied the type of glass (clear, absorptive, reflective) and the number of panes (single, double) with different combinations between the two skins. They found that DSF with a double reflective glazed outer skin and a single clear or single absorptive inner skin can lead to a 26% reduction in cooling load compared to a single skin façade with absorptive glazing.

Another design aspect of a DSF is the inclusion of a shading material between the two skins. Most DSF designs for the tropics include adjustable blinds that limit the amount of solar radiation that penetrates the inner skin. Gratia and De Herde experimented with the position of the blinds within the cavity as well as the color of the blinds [161]. They found that cooling load is less if the blinds are located in the middle of the gap as opposed to against one of the skins. They also showed that lighter colored blinds lead to a lower cooling load.

As the blinds heats up, they are cooled by the circulation of air through the gap which then is expelled to the outside. [138] used computational fluid dynamics approach to determine the optimum size of the gap between the skins in a naturally ventilated façade in Singapore. Interestingly, [136] found that there was only a slight reduction in cooling load for a mechanically vented DSF compared to a naturally ventilated DSF using the stack effect.

A DSF with moveable shading system was investigated in office building in both hot and cold climates. The investigations show that moveable shading reduces solar gains caused by gap overheating in traditional DSF. The shading reduces the gap overheating during summer and takes advantage of the solar gain (shading closed) in cooler climate [134]. The main obstacle in adopting this moveable shading DSF is the high cost of manufacturing and maintenance. Furthermore, steady state modelling may not be appropriate in such a quick climatic fluctuation and therefore non-steady state analysis should be considered (developed) [161].

A TRNSYS based simulation study was carried out of an office building located in subtropical Hong Kong to investigate the impact of glazing, window size and the orientation on façade performance [130]. The study found that the cooling load for a south facing façade for clear glazing is the highest followed by reflective and solar control glazing systems, which was found to be the case for all WWR values. A building with a double skin façade (DSF) had a lower cooling load compared to one with a single skin façade (SSF) for the same WWRs. By comparison, a building with a DSF and a large window area (WWR = 0.911) had the same annual cooling load as a building with a SSF and about a third of the window area (WWR = 0.32).

An impediment to DSF design includes an increase in construction cost. The payback period for the reduction in cooling costs to the initial construction costs can make the DSF not economically viable. The area inside the building that can be occupied will also be less for the same overall footprint compared to a single skin façade due to the extra space needed for the air gap between the skins. There are also higher maintenance costs for the internal blind system.

Application of DSF systems in the hot and humid climates can be highly promising. The key benefits of DSFs encompass: 'decreasing energy consumption', 'enhancing air ventilation, airflow', 'ameliorating the indoor thermal comfort conditions', 'improving the daylighting and glare control', 'enhancing the sound insulation, decreasing noise pollution and improving the acoustic condition' and finally, 'enriching the visual and aesthetic qualities' [132] (See Fig. 3).

6.2. Opaque façade

The DSF is mostly intended for office buildings to increase productivity and keep cooling costs down during the daytime. Residential buildings on the other hand are used differently. Not all rooms within a unit in the building are typically occupied during the day and some whole units may be vacant during this time. Therefore, the cooling needs and schedule are substantially different than office buildings and their design should reflect this. Chua and Chou [162] conducted a survey in Singapore and found that most people turn their air conditioners on at night and turn them off in the morning.

6.2.1. Insulation and thermal mass

Using the assumption of night-time occupation, Cheung et al. found through simulations that the cooling load would be reduced if the exterior walls had a higher thermal mass and thermal insulation was installed within the walls (See Fig. 4) [139]. Decreasing the WWR had a small effect of savings; the authors attributed this to the solar heat gain through the windows during the day that had dissipated before the time the air conditioners were used. Bojic et al. reinforced these findings with their own simulations for high-rise apartment buildings in Hong Kong [140–142]. Furthermore, they suggested that placing the insulation material against the inner wall had superior thermal advantages than installing against the external wall or centered between the inner and outer wall; a result was also seen by Ciampi and Tuoni [163].

6.2.2. Ventilated façade

The ventilated façade is made up of an interior and exterior wall with an air gap between them that is ventilated. The method of ventilation can be either through natural convection or by mechanical means. As the outer wall heats up the heat gain on the interior wall is limited through the ventilation [164,165]. The heat gain through the inner wall reduces as distance between the two layers is made larger [163,166].

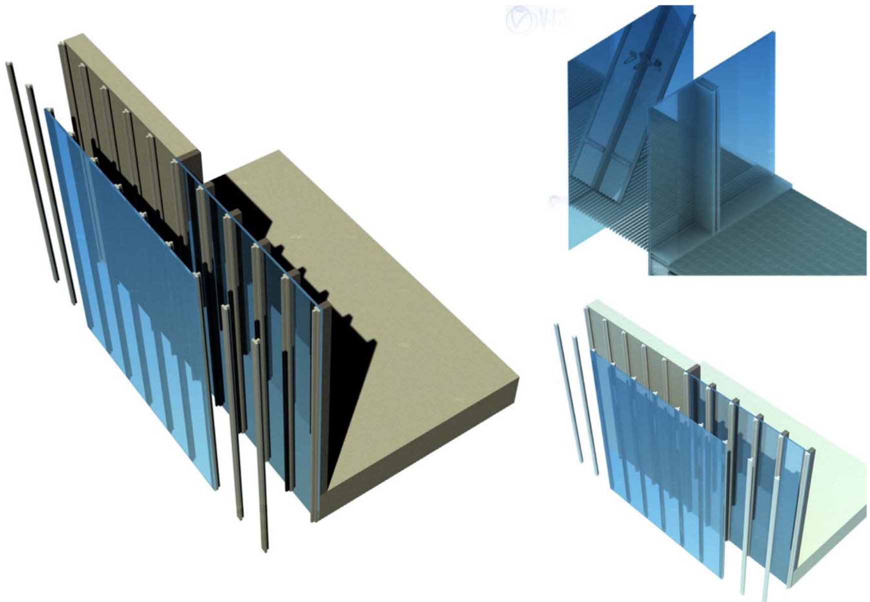

Fig. 3. Double skin façade (DSF) technical details in a schematic cut.

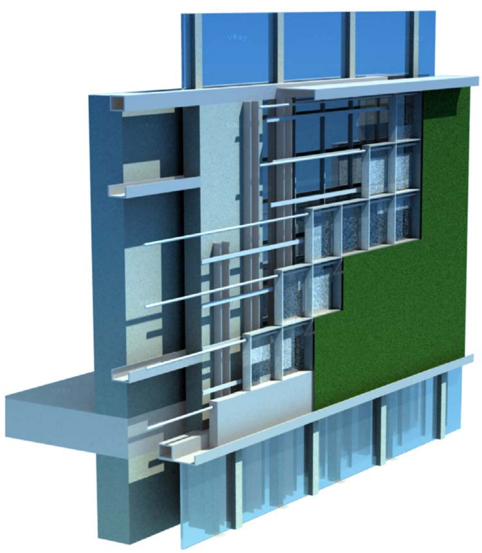

Fig. 4. Main layers of a typical vegetated facade in a schematic cut.

6.2.3. Façade albedo

Another important factor in a building's performance is the albedo of the envelope. In general, a lighter colored envelope will lead to less solar heat gain than a darker color [144]. For non-conditioned buildings, the higher albedo can lead to lower indoor air temperature and radiant temperature. In air conditioned buildings, an increase in albedo leads to a decrease in the required cooling load [139,154,167]. As the thermal resistance of the external wall material increases, the albedo of the outside wall becomes less important to the indoor heat gain. The roof albedo has a larger influence on the solar heat gain of the building than the walls.

6.2.4. Phase change material integration

Phase change materials (PCMs) are also finding their way into building envelopes [97,168–170]. PCMs are materials that go through a phase change, typically solid to liquid, when heating up so the transferred heat is a latent load instead of sensible one, effectively acting as lower density thermal mass. In hot climates, PCMs can help reduce the indoor temperature to reduce space cooling demand and shifting the cooling to off-peak times [96,133]. Alawadhi [171] found that by incorporating PCM into brick in a hot climate, the internal heat gain could be significantly reduced. In cooler climates for buildings with glazed facades heating savings can be found by using internal walls containing PCM [172]. Facades containing PCM are promising.

6.3. Photovoltaic façade

One of the more recent innovations for a façade is the building integration of photovoltaic materials. By integrating PV into the building envelope, the solar heat gain of the building is reduced and the generation of electricity can reduce running costs. An image of a building with a PV façade can be seen in Fig. 5.

6.3.1. Opaque photovoltaic façades

Most common and more commercially established PV cells are opaque and can therefore be integrated into opaque sections of the façade and shading devices [173–175]. Because the efficiency of PV

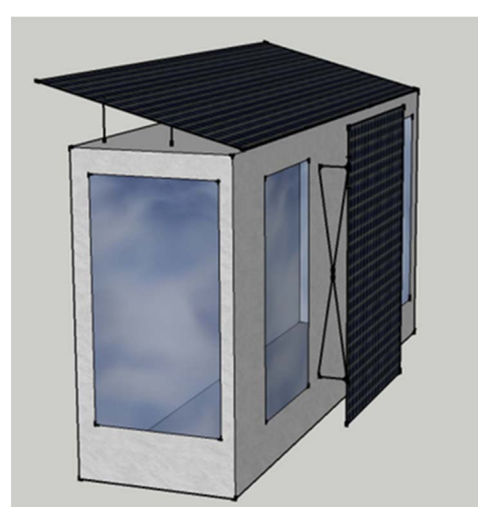

Fig. 5. A PV façade can be used to reduce heat gain and producing electricity by converting a portion of the incident radiation into electricity. A portion of the façade is covered in opaque PV material and is offset from the wall to allow for cooling of the PV panels. Here a semi-transparent PV material is used for the windows to allow natural lighting while still keeping the solar gain low.

modules goes down as its temperature rises, an air gap between the panels and the wall is needed. The PV layer with an air gap between it and the external wall acts as shading for the building and can greatly reduce the heat gain of the building and its cooling load, essentially acting as a ventilated facade. These would work well in tropical climates since the higher the insulation the greater percentage of reduction in cooling load. There is also some potential savings by using optical concentrating covers over the PV façade to reduce PV material and therefore costs [176,177].

6.3.2. *Semi-transparent photovoltaic façades*

A newer technology that is making its way into buildings are semi-transparent PVs that can be incorporated into glazing [128,178,179]. The benefits of semi-transparent PV systems include increased daylighting compared to more opaque façades, decreased heat gain compared to clear double-pane glass and on site electricity generation. However, the particular system has to be optimized for the particular climate. A larger PV window will produce more electricity but will also cause a higher heat gain, so a balance must be struck between daylighting, heat gain and electricity generation. Furthermore, as the temperature of the PV window increases, the electricity production efficiency of the PV system diminishes. Therefore, all of these parameters must be properly evaluated for climate in question.

Several types of semi-transparent PV systems have been compared with double-glazed windows in commercial buildings in Singapore [180]. The results showed that the major primary energy requirement in PV was in manufacturing PV modules. The energy payback time in this case was less than two years and return on investment can be as high as 35 times. The author also suggested to take great care in design of the windows as shading can cause poor electricity generation. Although, the cost of worst performing window can be recovered within 13 years.

7. Lessons from AEC industry

7.1. *Lessons from recent sustainable practices in Darwin, Australia*

At the end of 1974, most of the buildings in Darwin were destroyed by a cyclone because they were not designed for that type of weather event. When the city was rebuilt, there was a focus on structural strength and a need to build them quickly to house people who lost their homes. There was a large reliance on concrete blocks and slabs for construction material because of their quick assembly and structural integrity. The threat of a cyclone still exists so buildings are still made mostly from materials with high thermal mass for strength. Corrugated metal roofs are common for houses.

Houses in the Northern Territory must reach a minimum of a 5 stars and apartments 3.5 stars on the Nationwide House Energy Rating Scheme (NatHERS) be constructed; currently other types of buildings do not have to meet a minimum energy rating requirement. Owing to the climate of Darwin and the amount of solar radiation it receives, the WWR is kept low to prevent solar gain according to the building code. With high temperatures and humidity, residents of these houses resort to using air conditioning to maintain thermal comfort.

Much of the building code of Australia was designed for buildings in the south that have more temperate climates and rely on heating in the winter [53]. Therefore buildings are designed to seal houses up and prevent airflow and keep heat inside.

There is current trend in Darwin to design houses more suitable to the environment. This includes larger windows that are shaded to reduce solar heat gain but allow more cross-ventilation through the home to reduce reliance on air conditioning. However, the effectiveness of this concept has not yet been the subject of rigorous research. Such an observation should also apply to any type of buildings.

The award winning Darwin Convention Centre (DCC), Fig. 6, was designed to be aesthetically pleasing as well as energy conscious. The glass glazed façade on the western side allows occupants expansive views of the Darwin Waterfront while the metal shading allows filtered light to penetrate into the building while preventing unwanted heat gain.

Fig. 6. Western side of the Darwin Convention Centre. The exterior is a heavily shaded glazed façade to allow in filtered light but prevent unwanted heat gain.

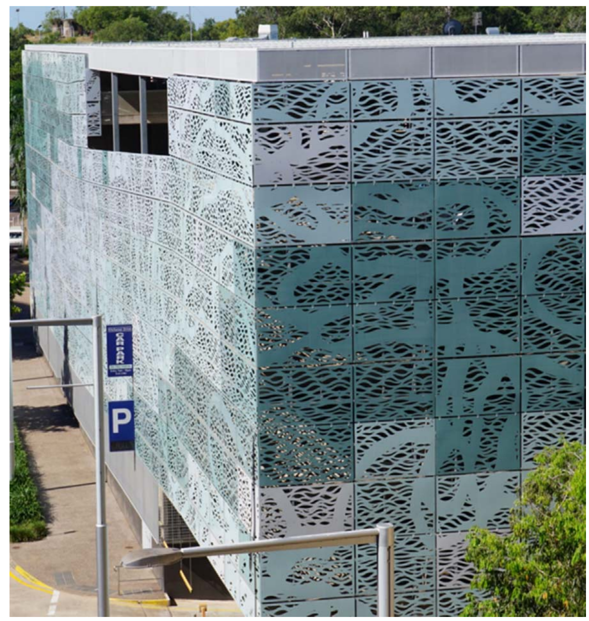

Fig. 7. Darwin Waterfront parking garage. The designed metal screens are used to prevent solar heat gain while still allowing natural ventilation.

The non-climate controlled Darwin Waterfront parking garage, shown in Fig. 7, features a decorative perforated façade to limit solar heat gain but still allow passive cooling through natural ventilation.

The Avenue Precinct is a combination of residential and commercial space that was built with sustainability in mind. As can be seen in Fig. 8, portions of the building use the vegetation on the façade as a means to reduce heat gain to the building and improve the appearance.

Fig. 8. The use of vegetation in the façade to reduce heat gain and add to the aesthetics at the Avenue Precinct, Darwin, Australia.

To date there has been no comprehensive data available on the energy performance of the buildings mentioned above and therefore the impacts of the façade and related designs on the buildings energy performance could not be quantified.

The Territory government is currently reviewing the local building code. The government established the Domestic Building Code Review Group in August 2015. The group is composed of local experts in home building and energy use design whose goal is to review the current building code and advise government officials of possible changes in the code. One of the group's goals is to make housing more responsive to climate change and improve energy efficiency. The report from their findings was due to the minister in early June 2016 but its contents are not yet public [181].

7.2. Lessons from recent sustainable practices in Kuala Lumpur, Malaysia

Looking at the energy consumption of office buildings in hot and humid climate of Malaysia, 50% of total energy consumption goes to air-conditioning, 25% is used for lighting and the remaining 25% to operate other small facilities [52]. In recent years, with the support of the Malaysian government, a number of highly energy efficient (office) buildings with innovative building façade design have been designed and constructed. These include: the Low Energy Office (LEO) and the Energy Commission (EC) Diamond Building, both located in Putrajaya, and the Green Energy Office (GEO), in Bangi. The key success of all these buildings is the significant reduction of energy consumption (with BEI 65–135 kWh m^{-2} yr^{-1}) compared to the conventional office buildings (with BEI 250 kWh m^{-2} yr^{-1}) in this context [182]. What these buildings have in common is that all have sun shading devices on their facades. In addition, the more recent GEO and Diamond buildings also have light shelves installed to direct more daylight deep into the buildings. The natural daylighting at the Diamond building is further enhanced with the installation of light shafts to bring daylight from the roof. These features are just some of the new developments which have happened around Kuala Lumpur. Historically however, architects designed building facades with features such as deep recessed windows, egg crate shaped, horizontal and/or vertical sun shading devices made of reinforced concrete or metal. Later in the 20thcentury, many buildings in Kuala Lumpur were designed primarily with deep reinforced concrete overhangs until the adoption of the international style in the 1980's onwards when buildings were designed with extensively glazed facades. In response to the climate, blinds, tinted glass and extensive air-conditioning are used to keep the interiors at thermally comfortable levels and keep the glare out.

Only more recently, Malaysia's most notable architect Ken Yeang – through his T.R. Hamzah and Yeang architecture firm – has developed the green façade through the Digi Data Centre building where vertical landscaping is utilized to insulate the façade while creating a more legible atmosphere around the vicinity of this building [183–185] (See Fig. 9). This building is the epitome of greenery usage on the façade at this point in time. Similarly, the Gardenwall towers designed by Kevin Low of Small Projects utilize a building-height permeable wall to allow plant growth to limit direct solar radiation while maintaining thermally comfortable spaces on the inside [186]. In addition, there are other smaller projects around the country using similar strategy but with small potted plants and creepers such as the Cage House by WHBC Architects which is an existing house that was fully covered with a new cage to allow growth of existing climbers to protect the house from direct solar radiation [187].

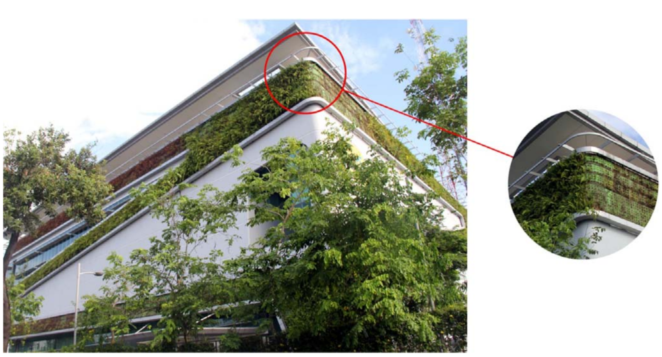

Fig. 9. Use of vegetated façade in Digi Data Centre (T.R. Hamzah and Yeang) in Kuala Lumpur, Malaysia.

Fig. 10. Incorporation of glazing façade, vertical vegetated structure and climbing plants in Le Nouvel KLCC in Kuala Lumpur, Malaysia.

The use of insulation in building façades in Malaysia is uncommon in any building typology and majority of new skyscrapers only employ double or triple glazing without much consideration towards sun-shading to keep excessive natural daylight and heat penetration at bay, all for aesthetic reasons and cost constraints. Only a handful of buildings were designed with the integration of effective light shelves on their façades (See Figs. 10–12). The Diamond Building benefited from the tilted angle of the glazed façade that does not allow natural daylight illumination on the façade for much of the day, thus limiting

Fig. 11. Full coverage of building façade with vegetation in Flora building in Kuala Lumpur, Malaysia.

Fig. 12. Use of screened façade as protective barrier in Science Faculty, University of Malaya in Kuala Lumpur, Malaysia.

the amount of heat that can penetrate through the glazed façade. Therefore, there is a need for installation of light shelves to reflect some daylight into the depth of this building. This building achieved the GBI and Green Mark Platinum rating and awarded the ASEAN Energy Award for its energy efficiency features. Other technologically advanced building skin materials such as ETFE (Ethylene Tetrafluoroethylene), sensor-controlled sun shading devices, light sensitive materials and transparent PV solar panels have not caught up in Malaysia due to prohibitive costs and maintenance issues.

Categorically, the façade design development in Kuala Lumpur can be divided into five distinct groups including projections on the façade, screened façade, fully-glazed façade, fully-clad facade and biologically protected façade. Commonly, the categorized façade designs help to reduce the transmission of heat into the buildings but with distinctively different methods as detailed in the following table. Each category has added benefits and weaknesses. Despite known issues such as durability and maintenance of its usage in the Tropical climate, there are two examples of the use of ETFE on the façade which are at the 1Mont' Kiara retail mall as glazed atrium roof and the LRT Subang – Kuala Lumpur Line that passes in between the Empire Shopping Gallery and the Saujana Residency as noise barrier. Their functionality effectiveness is yet to be determined by independent researchers other than the designers. Nevertheless, they represent an exciting glimpse into the future direction of façade design development in Kuala Lumpur (Table 2).

8. Discussions

8.1. Emergence of innovative building façades for integration in future buildings

The rapid advancement of building design, construction, and maintenance technologies has the potential to improve the performance of building façades which contemporarily defines the image of modern cities [188]. Likewise, advancement in Building Information Modelling (BIM) and Building Management Systems (BMS) makes it possible to properly incorporate building façades components for an optimized energy performance. In view of all these progressions, occupants' desire for elevated comfort levels is now becoming a major challenge. It is essential to promote innovative building technologies related to building façades (or envelopes in general) that accommodate both building energy optimization and enhancement of indoor conditions [189] while maintaining its aesthetic dimension. Advancement in computational techniques for Building Performance Simulation (BPS) that properly account for the building envelope is expected to lead to the realization of innovative building façade elements [189] and sustainable building standards.

To summarize, application of new building façade technologies need to consider the following aspects: (a) reduction of building heating, cooling, lighting energy consumption, (b) maintaining adequate natural lighting/visibility, (c) ensuring high thermal comfort standards and (d) proper management of daylight glare [189]. Luminescent solar concentrators (LSCs) integrate renewably energy resources in building façades [190], building integrated concentrating photovoltaics (BICPV) systems [191], bio-inspired adaptive building skins [83], highly dynamic building structures [192] and highly responsive, kinetic [193] and smart façades [194,195] are among emerging façade technologies and newly manifested design initiatives towards a resilient architecture. All these and other emerging technologies can potentially contribute to controlling building heat gain and

Table 2
Distinct categorization of building facades in Kuala Lumpur.

No.	Design type	Examples	Façade design details
1	Projections on the façade	a) Menara DBKL 2 b) Commercial outlet at Jalan Ampang c) Angkasapuri	1. The most classic solar radiation protection measure in the Tropical region; 2. Aligned with the passive solar architectural design that utilizesdeep overhangs/ projections to restrict direct sunlight illumination; 3. Allows good views from internal spaces; 4. Functional and decorative at the same time.
2	Screened façade	d) Science Faculty, University of Malaya	5. Utilization of metal/reinforced concrete/breeze blocks as screens in front of building façade as protective barrier; 6. Full protection against excessive solar radiation but restricts good views; 7. Lettable floor space reduced to allow for buffer space between building façade and protective screen.
3	Fully-glazed	e) Menara BSNs f) Embedded blinds in double glazing at the Malaysian GreenTech Corporation building	8. Utilization of glazing thermal property to restrict heat transmission; 9. Utilization of tinting film on the glazing/low emissivity glass/double or triple glazing; 10. Embedded blinds in double glazing; 11. Use of internal blinds for protection against glare and excessive heat; 12. Installation of internal light shelves to improve daylighting; 13. Less restriction to having good views.
4	Fully-clad facade	g) PETRONAS Twin Towers	14. Utilization of metal/foam board cladding for protection and insulation from solar radiation and/or frequent precipitation that causes leakages; 15. Enhancement of corporate image; 16. Full metal cladding adds to the urban heat island effect by reflecting heat and glare onto other buildings.
5	Biologically protected facade	h) Commercial outlet II at Jalan Ampang	17. Extensive planting on the façade with a layer of plant growth media; 18. Extensive planting insulates the façade from heat transmission; 19. Replacement of lost ecology on-site; 20. Mitigation of the urban heat island effect.

increasing energy storage/generation without compromising desired levels of occupants thermal/visual comfort.

8.2. The observed challenges and future direction of sustainable building façades

Admittedly, novel ideas to enhance the performance of façades in hot and humid tropics add much to the complexity of the already complex interactions between various architectural and engineering parameters, which makes the decision to adopt certain options more difficult. The parameters impacting (and being impacted by) the façade design are numerous, making it hard to develop a general principle or guidelines that cater for every design circumstance. As discussed in previous sections, various new concepts and technologies have emerged at various stages of development and could be directed towards solving one or more particular aspects of façade design. The introduction of new concepts or technologies into façade design of a building may in fact compromise other aspects of design and negate their benefits. Thus, an immediate challenge is to develop a credible tool or approach that assesses the performance of each of the façade design options.

In general, building codes in many jurisdictions offers two paths for compliance, namely: prescription and performance-based approach. Whilst prescription approach could be adopted relatively easily, it may not be cost- effective. Introducing any technology – be it emerging or proven – "*entails careful assessment of their economic feasibility, environmental benefits and effects on human comfort*" [196]. A performance based approach seems to offer more room for detailed assessment of the benefits of each option because it relies heavily on the availability of reliable computer packages and modellers. Detailed and precise mathematical models of each component are inseparable part of such packages. And since technologies advance in a very fast and dynamic manner, periodical updates of such packages and training of the modellers – which themselves could be economically prohibitive – need to be anticipated.

One of the main challenges of reducing energy consumption for cooling of buildings in hot and humid tropics is the extent of humidity level during wet and built up periods which last for up to six months (in case of Darwin). While there has not been conclusive evidence from rigorous research that show the impact of the humidity on the cooling energy demand, anecdotal evidence shows the heavy reliance on air conditioners to bring about thermal comfort during these humid periods. In such a case, the façade design principles that favour natural ventilation as the main cooling energy source may not be appropriate. During the high humidity period – which is also normally accompanied by relatively high temperature – occupants' thermal comfort could only be satisfied by bringing down both air humidity and temperature, a task that could be achieved only by mechanical cooling and dehumidifying systems. The cooling effect of natural ventilation mainly comes from the relatively high air speeds which is effective only when air humidity and temperature are relatively low – and only occurs during the dry season (in the case of Darwin). Thus, any benefit that passive cooling (natural ventilation) brings to building cooling during the dry season may be reduced or even have overall negative impacts by the need for more energy for cooling and dehumidifying during the hot and humid periods. Therefore, the challenge is to look for a façade design options that optimize passive cooling benefits and minimize the mechanical cooling energy demand during the wet season. For the same reason mentioned above, vegetated façades may not be an appropriate option for sites where humidity is the main concern for relatively long period.

Advancements in renewable energy technologies – in particular the PV systems and wind turbine technologies – have started to make their impact on the building sustainability. The main attractive feature of these technologies is their power producing capability which can potentially lead to self- sustaining buildings. Much research and development activities need to be done to improve system efficiency, reduce the system bulkiness and cost and to develop suitable technology that lead to their optimized integration into building façades. Due their locations, the solar azimuth angles of both Darwin and Kuala Lumpur mean that the vertical surfaces of facades will not benefit much from having building integrated PV. However, the buildings in both cities may still benefit from PVs installed on their roofs. The 1.25 MW PV system on the rooftop of Casuarina Shopping Centre, Darwin [197] and 4 MW rooftop system as part of the 19 MW system installed at Kuala Lumpur International Airport [198] are two examples of such systems in both cities.

Advancements in glazing, sensor and control technologies is expected to provide improved options for façade design, particularly in relation to visual comfort, reduced heat gain (or heat loss in cold climates), and aesthetics of the buildings façades.

The mode and extent of heat penetration into the building spaces through the opaque materials of building façades (and envelopes) can be modified through the selection of materials, which can insulate and absorb heat and therefore help dampen the room temperature fluctuation. Research on the potential application of PCMs as building construction materials are ongoing and if successful could have lasting impact on the building construction industry building codes and regulations.

On a matter directly relevant to hot and humid climates, humidity control is important in maintaining occupants' thermal comfort. As an alternative to conventional mechanical cooling and dehumidifying systems, solar thermally driven air conditioning systems could potentially provide cooling and dehumidification to buildings [199,200]. Whilst this is not directly related to the façade design, a separate humidity control provides greater flexibility for façade design options.

9. Conclusions

This paper presents a review of the energy conscious designs of façades of buildings in hot and humid climates with particular references to the cities of Kuala Lumpur, Malaysia, and Darwin, Australia. The paper has discussed the rising awareness and rapidly growing attention towards enhancing the energy performance of buildings as part of the sustainable development strategies of cities to combat climate change. The past and ongoing studies demonstrate the critical role of building façades as one of the fundamental constituents of the urban built environments in improving energy performance of buildings. The majority of the work reviewed draws attention to the need for healthier and more sustainable building façades, not only for attaining sustainable energy performance but also for attaining other features such as improved indoor comfort, well-being and satisfaction of the users. Escaping conventional approaches, previously regarded as being part of the building structure, facades are now designed independently from building structure to function towards protecting the indoor spaces.

There are three interrelated aspects involved when considering options for façade design in these particular climates. Firstly, building façades represent the physical appearance of buildings and therefore the façade aesthetic characteristics are central to the building presence at the location. Secondly, façades are a large part of the thermal boundary separating the indoor and outdoor environments. Through this function, façades play an important role in minimizing heat exchange between outdoor and outdoor environment that could significantly affect the building overall energy consumption. Lastly, hot and humid climates pose a particular challenge to the façade design options due to their significant sensible and latent load contributions to the overall energy consumption of a building. This entails a holistic approach in considering façade design options leading to attaining the building sustainability.

Recent advancements in a number of fields have brought about novel concepts and technological improvements that could be employed to enhance the performance of the building façades in this particular climate. On the other hand, the availability of various options makes it a complex and multifaceted task for the architects and engineers to identify the most appropriate approach. This clearly presents the need for interdisciplinary collaboration between architects and sustainable design experts during the early stage of building design.

Acknowledgements

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